

Galaxy Structure, Dark Matter, and Galaxy Formation

David H. Weinberg

*Ohio State University, Department of Astronomy, 174 W. 18th Ave.,
Columbus, Ohio, 43210, U.S.A.*

Abstract. The structure of galaxies, the nature of dark matter, and the physics of galaxy formation were the interlocking themes of *DM 1996: Dark and Visible Matter in Galaxies and Cosmological Implications*. In this conference summary report, I review recent observational and theoretical advances in these areas, then describe highlights of the meeting and discuss their implications. I include as an appendix the lyrics of *The Dark Matter Rap: A Cosmological History for the MTV Generation*.

1. Introduction

What is the structure of galaxies? What is the dominant form of dark matter in the universe? How did galaxies form? As Paolo Salucci explained in his introductory remarks, an organizing principle of the DM 1996 meeting was to emphasize the connections between these three issues, in particular to place an empirical understanding of galaxy structure at the heart of studies of dark matter and galaxy formation. While I do not think that the full story of galaxy formation can simply be read out of observed galaxy properties, it was clear during this meeting that advances of the past few years allow much closer links between theoretical accounts of dark matter and galaxy formation and observations of the Milky Way, nearby galaxies, and high redshift objects.

In the next section, I will describe some of the observational and theoretical advances that set the scene for DM 1996. I will then review some of the meeting highlights and discuss their implications for the structure and formation of galaxies and the nature of dark matter. I will close with a discussion of prospects for observational progress in the next few years. To complete my introduction, I would like to list some of the other questions that I had in mind when listening to the conference talks and composing my summary report. These questions are narrower in scope than the three mentioned above, but we surely will not feel satisfied with our understanding of galaxies and dark matter until we can answer them all.

- Do the observations interpreted as evidence for dark matter actually reflect a breakdown of general relativity?
- Is baryonic dark matter a dynamically important component of galaxies?
- Is there non-baryonic dark matter?

- How far do dark halos extend?
- What are the profiles and shapes of the luminous and dark mass distributions in galaxies?
- What is the origin of the Tully-Fisher relation?
- What environments did the oldest stars form in?
- What are typical merger histories for different galaxy types?
- What determines a galaxy's luminosity, morphology, color, surface brightness, and other properties?

2. Recent Advances

There have been a number of important advances in the last few years, both observational and theoretical, on the subjects of galaxy structure, dark matter, and galaxy formation. These advances set the scene for DM 1996, and many of the talks presented reviews and updates of these achievements.

2.1. Observational Advances

- The Discovery of MACHOs – Paczynski's (1986) proposal to detect massive objects in the Galactic halo through gravitational microlensing of background stars seemed, in 1986, brilliant in principle but implausibly difficult in practice. The dramatic success of microlensing searches is a tribute to the guts, cleverness, and perseverance of the experimenters. This technique has opened up vast opportunities in the studies of dark matter, Galactic structure, stellar populations, and stellar evolution. As discussed by FREEMAN and in §3 below, the 2-year results from the MACHO experiment are quite surprising, and we do not yet know whether the search has detected the primary constituents of the Milky Way's dark halo.
- The Systematics of Spiral Rotation Curves – An epochal advance of the 1970s, beautifully reviewed here by VAN ALBADA, was the realization that galaxy rotation curves are not Keplerian in their outer parts but flat. This transformation of views moved the dark matter problem to astronomical center stage. Over the past few years we have come to appreciate that rotation curves are not truly flat after all. Some rise slowly and continuously, others rise sharply in the middle and decline in the outer parts, and the shape of a galaxy's rotation curve correlates strongly with its luminosity and circular velocity. These developments do not eliminate the need for dark matter, but they do make the tales of "conspiracy" between galaxies' luminous and dark components more complicated. Many investigators have contributed to this new understanding of rotation curves (see, e.g., Salucci & Frenk 1989; Casertano & van Gorkom 1991; Persic & Salucci 1991). The "Universal Rotation Curve" paper of Persic et al. (1996) brought together an enormous quantity of data in a systematic and powerful way. The existence of a universal rotation curve has deep implications

that are not yet fully digested, though a number of talks in DM 1996 gave evidence that people are grappling with them. It will be crucial for future observational studies to explore the limitations of the Persic et al. (1996) characterization of rotation curves by examining the degree of scatter at fixed luminosity, by correlating deviations with other galaxy properties, and by using more HI data to better tie down rotation curve shapes in the outer parts.

- **Satellite and Lensing Evidence for Extended Halos** – Binary galaxy studies have long suggested that dark halos extend beyond the radius probed by HI measurements, but the studies of satellite galaxies by Zaritsky and collaborators (Zaritsky et al. 1993; Zaritsky & White 1994) made this result much firmer and more quantitative. From the velocity distribution of satellite companions, they concluded that the rotation curves of L_* spirals remain approximately flat out to radii of at least 200 kpc. More recently Brainerd et al. (1996) reached a similar conclusion by studying the weak lensing of background galaxies by foreground dark halos, reviving an approach first tried by Valdes et al. (1984). While their initial analysis yielded only a $\sim 2\sigma$ detection of extended halos, this technique appears to have great potential for application to larger data sets, and it could perhaps be extended to study the shapes and profiles of dark halos. At DM 1996, ZARITSKY presented the latest update of the satellite work, using a sample nearly double the size of Zaritsky et al.’s (1993).
- **A Partial Consensus on Galaxy Evolution at $z \leq 1$** – During the 1980s and early 1990s, the evidence of galaxy evolution seemed to become more confusing and contradictory with each new paper on number counts or faint galaxy redshifts. In the last couple of years, a unified picture has emerged that seems capable of explaining a wide range of results from ground-based and HST studies: the more luminous, redder galaxies show little evolution between $z = 1$ and the present, but the population of fainter, bluer galaxies with late-type morphologies and emission-line spectra evolves very rapidly. These blue galaxies must have been either more luminous or more numerous at $z = 0.5$ than they are today. There is still no clear consensus on what these objects evolve into, though low surface brightness dwarfs are one popular candidate. There is also an intriguing recent study that challenges the account of early-type galaxies. Kauffmann et al. (1996) applied a V/V_{\max} test, incorporating passive evolution effects, to the red galaxies in the Canada-France Redshift Survey (Lilly et al. 1995), and they concluded that 2/3 of the luminous, early-type galaxies were missing from the sample at $z \sim 1$, either because they were broken into fainter subunits or because active star formation had altered their colors.
- **Metals in the Lyman-alpha Forest** – The traditional view of quasar absorbers had long distinguished “metal-line” systems, associated with high HI column densities, from the lower column density “Ly α forest” systems, which were usually thought to be of primordial composition. Then came the Keck telescope, the HIRES spectrograph, and studies revealing heavy element absorption in at least 50% of “forest” lines with $N_{\text{HI}} > 3 \times 10^{14} \text{ cm}^{-2}$ (Cowie et al. 1995; Womble et al. 1996; for earlier evidence

of metals in the forest see Meyer & York 1987). Even HIRES has difficulty reaching to lower column densities, but current results are consistent with a metallicity ~ 0.01 solar in all Ly α forest systems. If the absorbers reside in galaxies, then metal enrichment is no great surprise, but if the simulation-based picture that I described in my contributed talk is correct, then most of the forest lines are produced by intergalactic gas (see Cen et al. 1994; Zhang et al. 1995; Hernquist et al. 1996). In this case the detection of metals implies that the primordial gas was ubiquitously enriched by early star formation before the formation of most galaxies. This conclusion is not implausible, but it is profound, and it will be interesting to explore its consequences and to try to test it against observations of low metallicity stars in the Milky Way.

2.2. Theoretical Advances

- The Cluster Baryon Argument – This simple but powerful argument, originally due, I believe, to Simon White, draws a connection between the baryon density parameter Ω_b and the mass density parameter Ω . In standard scenarios of structure formation, the ratio of baryonic mass to total mass within the virial radius of a rich cluster should be close to the global ratio, and observed ratios therefore set a lower limit (since some of the baryons could be dark) to Ω_b/Ω (White et al. 1993). Combining with nucleosynthesis estimates of Ω_b , one obtains an upper limit on Ω . As I will discuss in §3, this argument has begun to shake theorists’ faith in a critical density universe, and it raises the stakes in studies of the primordial deuterium abundance.
- A Universal Density Profile from Hierarchical Clustering — Navarro, Frenk, & White (1996; hereafter NFW) used high-resolution N-body simulations to show that collisionless collapse in hierarchical clustering models produces a universal form for the halo density profile, $\rho \propto r^{-1}$ in the inner parts bending gradually towards $\rho \propto r^{-3}$ in the outer regions. The concentration of the halo, defined, for example, by the ratio of the scale radius where $\rho \propto r^{-2}$ to the virial radius within which the overdensity is ~ 200 , depends systematically on cosmological parameters and on the halo’s collapse redshift, leading to a tight correlation between the amplitude and shape of galaxy rotation curves. It is obviously tempting to view the “Universal Profile” as the theoretical counterpart to the “Universal Rotation Curve” discussed above, and the one may well prove to be the explanation of the other. The combination of a universal shape with a concentration that depends on collapse redshift suggests a way to unify the “violent relaxation” and “secondary infall” accounts of gravitational collapse (White 1996), and the NFW profile offers a natural way to reconcile strong gravitational lensing with large X-ray core radii in rich clusters. As a caveat, I should note that there is not yet complete consensus within the N-body community on the form of the density profile or the degree of scatter at fixed mass. NAVARRO showed new results from this work, which I discuss briefly below, and RIX showed the power of incorporating this kind of physically motivated halo profile into modeling of observations.

- Monte Carlo Models of Galaxy Formation and Evolution — Kauffmann et al. (1993) and Cole et al. (1994), building on the ideas of Press & Schechter (1974), White & Rees (1978), and White & Frenk (1991), developed a remarkably rich, semi-analytic formalism for modeling galaxy formation in hierarchical clustering models. This approach allows the kind of population synthesis and chemical evolution calculations discussed by CHIOSI and MATTEUCI to be placed within a realistic framework describing the collapse and merging of dark matter halos and the cooling of gas within those halos. The most important qualitative lesson to emerge from these studies is that a galaxy’s star formation history and assembly history may be two quite different things, as much of the star formation can occur in sub-units that only later merge to form the final galaxy. Thus, even though the mass scale of typical collapsed objects grows with time, a hierarchical model predicts blue dwarf irregulars and red giant ellipticals because the low mass objects that survive as such today collapsed relatively recently, while the massive objects formed by mergers in dense regions, where the first collapse of star-forming systems happened early. There are free parameters and approximations in the Monte Carlo models, but they can make contact with a wide variety of observations, and they provide a theoretical framework within which one can quickly assess the effect of changing the cosmological scenario or altering the assumptions about star formation and “microphysics” (cooling processes, metal enrichment, feedback, etc.). FRENK’s review described the Monte Carlo methods and presented some recent results, and the talks by FIRMANI, AVILA-REESE, and MENCI showed that others are making use of this general approach, developing extensions and finding new applications.
- Support for the White/Rees Scenario in Cosmological Simulations — Collisionless mergers quickly erase substructure, so a purely gravitational account of galaxy formation cannot explain the existence of rich clusters containing dozens or hundreds of galaxies. White & Rees (1978) emphasized this problem and proposed the now canonical solution: dissipation concentrates the baryons within their dark halos, creating tightly bound units that can survive long after the halos themselves merge. Timescale arguments based on spherical collapse suggest that the required cooling should occur rapidly enough, and numerical simulations have recently achieved the dynamic range and physical sophistication needed to demonstrate this process in action, showing the transition from realistic cosmological initial conditions to radiatively cooled gas clumps that have masses and overdensities comparable to the baryonic components of galaxies (Katz et al. 1992; Evrard et al. 1994; Summers et al. 1995; Katz et al. 1996). JENKINS et al.’s poster presented some results from state-of-the-art cosmological hydrodynamics simulations; with the computational firepower afforded by parallel machines, one can go directly from the primordial fluctuations of a cosmological theory to the clustered galaxy distribution, predicting rather than imposing its relation to the underlying distribution of mass. Higher resolution simulations of individual galaxy collapses reveal the complexity of the galaxy assembly process and suggest clues to the origin of the Hubble sequence (e.g., Katz & Gunn 1991; Katz 1992; Navarro & White 1994;

Vedel et al. 1994; Steinmetz 1995; Navarro & Steinmetz 1996; GELATO and GOVERNATO in these proceedings). Numerical simulations have played a valuable role in calibrating the assumptions used in the Monte Carlo models, and as the simulations improve the interplay between these approaches should become even more fruitful. I suspect (and hope) that $\text{Ly}\alpha$ forest simulations like those described in my contributed talk will also turn out to be an important theoretical advance (see Hernquist et al. 1996 and Weinberg et al. 1996 for written accounts of this work). They are somewhat off the main theme of this conference, but they do offer further support for the scenario of hierarchical structure formation, and if the promising initial results survive tougher scrutiny, then a new class of observations, high-resolution quasar spectra, will become available as tests of cosmological models.

3. Some Meeting Highlights

For anyone who has conferenced with Carlos Frenk in years past, the most astonishing event of DM 1996 was his declaration (in the discussion following GIRARDI's talk) that "There is no reason to think that Ω equals one." This comment demonstrates the power of the cluster baryon argument (see §2) to shake views once stoutly defended — there are no obvious minor fiddles to the standard scenario that circumvent the argument apart from lowering Ω .

I list below a few of the other results that I considered highlights of the meeting, in chronological order of presentation. In the sections that follow, I will discuss implications of these results and others presented at DM 1996 for our understanding of galaxy structure, dark matter, galaxy formation, and the Tully-Fisher relation.

Navarro: Halos in $\Omega = 1$ CDM models are too concentrated to fit the observed rotation curves of dwarf irregulars and low surface brightness (LSB) spirals. Low- Ω models yield better fits. Decomposing observed rotation curves assuming the NFW profile for the dark halo collapses most of the scatter in a plot of concentration vs. circular velocity (r_s/r_{200} vs. v_{200} , where r_s is the NFW scale radius, r_{200} the virial radius, and v_{200} the circular velocity at r_{200} .)

Moore (1994) and Flores & Primack (1995) had argued that the gently rising rotation curves of dwarf galaxies were inconsistent with the r^{-1} central cusp of Dubinski & Carlberg (1991) and NFW, emphasizing this discrepancy as a challenge to the hypothesis of CDM halos. Navarro showed that the same problem appears for giant LSB spirals, making it more difficult to invoke exotic feedback effects as a possible solution. But he also showed that low- Ω CDM models produce lower concentration halos (larger r_s/r_{200} at fixed v_{200}), in better agreement with observed rotation curves, and he argued that slowly rising rotation curves therefore challenge the $\Omega = 1$ CDM model rather than the hypothesis of cold, weakly interacting dark matter *per se*. Disk/bulge/halo decomposition of the rotation curves in Navarro's sample yields little scatter in the relation between concentration and circular velocity for the parent halos, a hint that the predictions of NFW's numerical simulations may apply to the observed universe.

Freeman: The best fit to the results of the MACHO experiment, assuming a “standard” Galaxy halo, implies a MACHO mass $m = 0.5M_\odot$ and a MACHO halo fraction $f = 0.5$. MACHOs with $3 \times 10^{-7}M_\odot < m < 0.03M_\odot$ have $f < 0.2$.

The eight microlensing events observed towards the LMC indicate a large population of objects whose nature is quite mysterious. The mass is right for white dwarfs, but deep HST images reveal no such population (Flynn et al. 1996), and chemical evolution constraints make any population of stellar remnants an unlikely candidate for MACHOs (Charlot & Silk 1995; Adams & Laughlin 1996). Given the statistical and systematic uncertainties, the detected MACHOs could represent a small fraction of the dark halo or the whole thing. The absence of short-timescale events rules out sub-stellar objects as the dominant contributors to the dark halo, at least if the standard halo model is approximately correct. Two years of MACHO data have raised numerous questions about the Galaxy’s structure and constituents. Improved statistics, monitoring of ongoing events, and searches for microlensing in other galaxies (as discussed by CROTTS and GONDOLO) should guide us towards answers over the next couple of years.

Tytler: The deuterium abundance in two high-redshift QSO absorbers implies a baryon density parameter $\Omega_b = 0.024 \pm 0.002h^{-2}$.

Tytler reviewed the arguments of Tytler et al. (1996) and Burles & Tytler (1996) for a primordial deuterium-to-hydrogen ratio $(D/H)_P = 2.4 \pm 0.3 \times 10^{-5}$, and he argued that higher values obtained by some other groups are probably a result of contamination by intervening HI. Rugers & Hogan (1996ab), by contrast, suggest that $(D/H) \sim 2 \times 10^{-4}$ is the primordial value and that other observations obtain lower ratios because of deuterium destruction. Combined with big bang nucleosynthesis arguments, the low $(D/H)_P$ implies a baryon density about double the value of $\Omega_b = 0.0125h^{-2}$ found by Walker et al. (1991), while the high $(D/H)_P$ implies about half this density, $\Omega_b \approx 0.006h^{-2}$. I don’t yet find either set of observational interpretations completely compelling. Tytler’s value of $(D/H)_P$ is easier to understand theoretically, at least if one is willing to expand the quoted observational error bars on $(^4\text{He}/H)_P$. With the Rugers & Hogan (1996ab) abundance, it is difficult to explain why (D/H) in the local ISM is more than an order of magnitude lower, difficult to reconcile the cluster baryon argument with the density parameter $\Omega > 0.2$ suggested by large-scale structure studies, and difficult reproduce the observed mean opacity of the Ly α forest (Hernquist et al. 1996).

Fontana: A multi-color search for high redshift galaxies has detected 11 galaxies with $3 < z < 4$ and 5 galaxies with $z > 4$, including one with $z = 4.84$.

The Lyman-break method of finding $z > 3$ galaxies has truly come into its own in the last year now that spectroscopic confirmations show that a large fraction of candidates are genuine high- z objects. These searches are finally revealing a population of “normal” galaxies at redshifts previously reached only by quasars and radio galaxies.

Theuns: 40% of stars in the Fornax cluster are intergalactic.

Direct searches for intergalactic background light in galaxy clusters are notoriously difficult. Theuns & Warren (1996) took the innovative approach of using

narrow-band filters to look for intergalactic planetary nebulae. They found 10 strong candidates in Fornax, and after scaling by the ratio of normal stars to planetary nebulae, they estimate that 40% of the cluster's stars lie outside of galaxies. Freeman reported that an Australian collaboration has found a similar result in the Virgo cluster. These are striking observational results, though it is not too hard to imagine that tidal stripping and disruption could produce a large population of intergalactic stars in clusters. GALLAGHER emphasized that galaxy clusters are hostile environments for dwarf ellipticals. Perhaps Theuns & Warren are seeing the remnants of those that did not survive.

Zaritsky: The velocity difference ΔV between a satellite and its spiral primary is nearly uncorrelated with the line width W of the primary.

This result was reported in the original Zaritsky et al. (1993) paper, and it is now confirmed in a larger sample. In the meantime, a possible theoretical interpretation has emerged, since the systematic dependence of halo concentration on circular velocity found by NFW means that a small range of v_{200} maps into a much larger range of linewidths measured near the optical radius. While the number of satellites is probably too small for a detailed quantitative test, this qualitative explanation of an otherwise puzzling observation is one of the best pieces of empirical evidence for the NFW profile. A similar explanation can be constructed from the Persic et al. (1996) universal rotation curve, if one extrapolates the rotation curve trends seen near the optical radius to the outer halo.

Olling: The flaring of the HI disk in NGC 4244 implies that its dark halo is highly flattened, with an axis ratio of about 5:1.

Disk flaring in highly inclined galaxies is one of the few ways of estimating halo flattening, and Olling's observations and modeling of NGC 4244 define the state of the art (Olling 1996ab). His conclusion that the halo is highly flattened depends on the assumption that the gas velocity dispersion tensor is isotropic. The observational data do not provide a way to test this assumption directly, but Olling argued that it is likely to be correct because the cloud collision time is a small fraction of the galaxy's age. Olling is acquiring data for seven additional galaxies, so we will soon know whether this striking result is found in a large fraction of spirals.

Rix: Elliptical galaxies have comparable amounts of luminous and dark matter within the effective radius.

It has been difficult to establish the presence of dark matter in the inner parts of ellipticals because the orbit population is not known. Observations that measure the full line-of-sight velocity distribution out to several effective radii are finally beginning to crack the problem, demonstrating that models with constant mass-to-light ratio cannot fit the data. Assuming an adiabatically contracted, NFW halo, Rix finds that the luminous and dark mass are about equal within R_e and that the circular velocity stays roughly constant across the luminous-to-dark transition.

Frenk: Monte Carlo models of galaxy evolution in the $\Omega = 1$ CDM model reproduce the observed redshift distribution of $B < 24$ galaxies, the evolution of the luminosity function seen in the Canada-France Redshift Survey, and the properties of $z > 3$ galaxies studied by Steidel et al. (1996).

For many years, the standard CDM model had a reputation for forming galaxies much too late. However, while this model does have a great deal of activity at $z < 1$, it appears that it fits the observations in this regime and, more remarkably, also accounts for the population of star-forming, Lyman-break galaxies at high redshift. The same kind of modeling should soon lead to predictions for other cosmological scenarios.

Zabludoff: 75% of “E+A” galaxies are in the field.

A long-standing question has been whether the E+A phenomenon — a spectrum showing a recent but not ongoing starburst superposed on an old stellar population — is confined to galaxies in rich clusters, perhaps implicating interaction with the intracluster medium as the starburst trigger. Zabludoff’s study (Zabludoff et al. 1996) answers the question definitively, in the negative, suggesting that the phenomenon is instead triggered by galaxy-galaxy interactions.

4. The Structure of Galaxies

What is the structure of the main dynamical components in disk galaxies? A “traditional” account, dating from the 1970s but still widely used, might include an $R^{1/4}$ -law bulge, an exponential disk, and a spherical, isothermal, dark halo with a constant density core. Recent observational and theoretical developments, many of them discussed at DM 1996, suggest a “modified traditional” account: an exponential bulge (BROEILS; Courteau et al. 1996), an exponential disk, and a moderately flattened, possibly triaxial halo with an NFW profile adiabatically compressed by the luminous matter. Of course the NFW profile is only the prediction of a specific class of theoretical models, but it is important to recognize that existing data are compatible with this and probably many other forms for the halo profile, and that theory gives no particular reason to expect isothermal halos with flat cores (especially after they have been gravitationally compressed by the luminous matter). Conventional halo fitting parameters like the core radius and central density may have more to do with the history of the field than with the physics of galaxies.

A few speakers discussed more radical views, such as dark matter in a highly flattened halo or thick disk (OLLING; PFENNIGER), or galaxies governed by non-Newtonian dynamics with no dark matter at all (RODRIGO-BLANCO; GRIV). VAN ALBADA made the cautionary point that most high-quality, extended rotation curves can be explained quite adequately by applying MOND (Milgrom 1983) to the luminous component and detected HI disk, or by applying Newtonian gravity to the luminous component and a constant multiple (~ 10) of the HI disk. The assumptions are unconventional, but these models produce good fits to the data with fewer free parameters than the traditional bulge/disk/halo decomposition. COTÊ presented an important class of counterexamples to the scaled HI fits: in dwarf galaxies whose rotation curves are measured out to many disk scale lengths, the ratio of the HI surface density to the inferred mass density plummets beyond the Holmberg radius. This result does not rule out the possibility of a dark matter disk, but it weakens the force of the argument by coincidence. One-dimensional rotation curves have limited power to constrain multi-dimensional, multi-component mass distributions, and

it is therefore important to pursue complementary constraints from modeling of bars (DE BATTISTA), warps (KUIJKEN), faint stellar halos (FUCHS), polar rings (ESKRIDGE), or two-dimensional velocity fields (SCHOENMAKERS; MENDES DE OLIVEIRA).

The structure of elliptical galaxies is still more difficult to pin down because of the absence of dynamically cold tracers. Nonetheless, X-ray data, gravitational lensing, kinematic studies of globular clusters, and rotational velocities of occasional HI rings all indicate the presence of extended dark halos, and stellar dynamical evidence now indicates comparable amounts of dark and luminous mass within the effective radius (DANZIGER; RIX; SAGLIA; VINE). Modeling observations with adiabatically squeezed, NFW halos, RIX infers circular velocities $v_{200} \geq 400 \text{ km s}^{-1}$ for two L_* -ish galaxies, suggesting that the dark halos of ellipticals are more massive than those of spirals of similar luminosity. PRUGNIEL argued that the small tilt of the fundamental plane is explained by a combination of changes in stellar population, rotational support, and profile shape with luminosity, concluding that the ratio of total mass to visible mass in the inner parts of ellipticals is independent of luminosity. The strong evidence for “normal” dark halos in ellipticals argues indirectly against dark disks in spirals, since the dark matter would need to be dissipative in one class of galaxies but not in the other.

5. The Nature of Dark Matter

What is the dark matter? Traditional ideas include faint main-sequence stars, sub-stellar objects, and cold, weakly interacting particles. The first of these possibilities has been ruled out by the paucity of faint stars in deep HST images (Bahcall et al. 1994; Flynn et al. 1996). The second now appears to be ruled out by the absence of short-timescale events in the MACHO data, at least for a standard halo model (FREEMAN). The third idea, beloved of particle physicists and of cosmological theorists like myself, is harder to kill.

A number of alternative ideas were discussed at DM 1996. The MACHO results have revived the popularity of stellar remnants as a dark matter candidate, but it remains difficult to see how one could process 90% of the baryons in the universe into compact objects without violating observational constraints on the chemical abundances of halo stars and the luminosities of galaxies at high redshift. FREEMAN suggested that the MACHO experiment might instead be detecting a population of primordial black holes. It would be rather mysterious if objects formed a fraction of a second after the big bang happened to lie in the mass range of typical stars, but sometimes a coincidence is just a coincidence. PFENNIGER made an impressive case for fractally clumped molecular gas as dark matter, and FIELD & CORBELLI’s poster described some closely related possibilities. These ideas have the virtue of making some interesting, observationally testable predictions. However, while one can easily imagine clumpy gas hiding itself in spiral disks, it seems less natural as an explanation for dark matter in elliptical galaxies or in galaxy clusters. There is also the long-standing argument that baryonic dark matter alone cannot explain dynamical estimates of Ω without doing violence to big bang nucleosynthesis. This argument holds even

with TYTLER’s lower estimate of the primordial deuterium abundance, though the implied gap between Ω_b and Ω is no longer quite as convincing.

Warm elementary particles were discussed as a possible explanation for slowly rising rotation curves, though NAVARRO argued that one could also match these observations with cold dark matter in a low density universe. SOLENG discussed three rather more exotic possibilities from theoretical particle physics: a cosmological constant, an oscillating gravitational constant, or a string fluid. These forms of stress-energy have negative pressure, and by accelerating the cosmic expansion at late times they would help reconcile the estimated ages of globular clusters with estimated values of the Hubble constant. The first two would not cluster gravitationally, so they could not be the dark matter in galaxies and galaxy clusters, but they could still reconcile a low dynamical Ω with the flat universe preferred by inflation models. I have previously been rather skeptical of the cosmological constant as a solution to the age problem — it seems so cheap — but there are many possibilities lurking in string theory and extensions of the standard particle model for negative-pressure fields that would act like a time-variable Λ (see, e.g., the discussion in Wilczek 1997). The more I hear about them, the more my resistance weakens.

There remains the heretical alternative to any form of dark matter, changing the theory of gravity. Speaking for myself, I believe firmly in dark matter six days a week, and on the seventh day, I waver. We cannot happily dismiss the alternative-gravity hypothesis until we have detected the dark matter by non-gravitational means (or by microlensing, since its lengthscale and acceleration regime is completely different from that in which the dark matter problem manifests itself). However, while the direct, high-precision tests of general relativity are confined to scales much smaller than galaxies, the conventional GR + dark matter scenario receives enormous indirect support on larger scales from its successful account of gravitational lensing, from the multiple empirical successes of the big bang theory, and from the more limited but still significant success of gravitational instability theory in explaining the transition from microwave background fluctuations to galaxies and large-scale structure. It seems unlikely that a relativistic generalization of non-Newtonian gravity would preserve these achievements, though conceivably the departures from GR could be linked to cosmology in a way that suppresses their magnitude at early times. (It is a notable coincidence that the characteristic acceleration in Milgrom’s MOND formulation is approximately equal to the speed of light multiplied by H_0 .) I think that non-Newtonian gravity received about the right amount of attention at DM 1996: discussed in a few talks and posters (RODRIGO-BLANCO; VAN ALBADA; GRIV) and mentioned in comments and questions, but not a dominating theme.

6. Galaxy Formation

How did galaxies form? Many talks presented numerical or semi-analytic illustrations of “the CDM view” of galaxy formation. The growth of structure in the dark matter distribution is hierarchical and complex. Gas cools and forms stars in sub-galactic and galactic mass halos. Halos merge rapidly in groups and clusters, but the denser, gaseous/stellar components merge more slowly. Roughly

speaking, this is the White & Rees (1978) scenario, though there is probably greater appreciation today of the variance in halo merger histories and of the influential role of tidal fields and filaments in organizing and guiding gravitational agglomeration. The broad features of this picture are common to the many post-COBE variations on “standard” CDM — tilted spectrum, low Ω , mixed dark matter, and so forth — and some of these features would probably survive in other cosmological models.

The main point of contention in recent theoretical studies has been the importance of supernova feedback. The majority view is that feedback plays a critical role in suppressing the formation of faint galaxies, and perhaps in controlling the rates of gas cooling and star formation and in suppressing the transfer of angular momentum between the baryons and the dark matter. Dissenters (e.g., Katz, Hernquist, and I) have assigned feedback a more limited role, arguing that energy deposited by supernovae cannot travel far in the dense gaseous environment of a forming galaxy. I don’t know which of these points of view will ultimately prove closer to the truth, but just for fun I will state an unequivocal prediction: when the detailed, compelling theory of galaxy formation that we are groping towards today emerges in its full glory, supernova feedback will not play a major role in determining the global properties of galaxies, except for the lowest mass systems ($v_c \leq 50 \text{ km s}^{-1}$ in round numbers).

The CDM picture of galaxy formation has some empirical support from observations of high-redshift galaxies (e.g., FILLIPI et al.; FRENK) and from the aforementioned successes of the NFW profile in explaining rotation curve shapes and satellite dynamics. However, one could hardly claim that current observations dictate such a picture. The strength of the CDM scenario is that it provides a plausible account of galaxy formation that is integrated with evidence from microwave background anisotropies, large-scale structure, and the Ly α forest. It is worth noting that if all dark matter *is* baryonic then we have no good *a priori* theory of galaxy and structure formation. An attraction of primordial black holes as dark matter is that they could explain the MACHO results while preserving the successes of the CDM scenario. Because they would form in the very early universe, they would allow Ω to exceed Ω_b without requiring any new elementary particles.

7. The Tully-Fisher Relation

The Tully-Fisher relation lies at the nexus of my three organizing themes, and it was a recurring motif in many of the talks, posters, and informal discussions at DM 1996. Typical estimates of the Tully-Fisher scatter in large samples are $\sigma \sim 0.35 \text{ mag}$ (Strauss & Willick 1995). For his sample of spirals in Ursa Major, VERHEIJEN finds a scatter of 0.26 mag in the K-band Tully-Fisher relation, and after accounting for observational errors he estimates an *intrinsic* scatter of just 0.12 mag. The results of Bernstein et al. (1994) for a sample of 25 spirals in the vicinity of Coma are even more remarkable: they obtain an *observed* scatter of 0.12 mag, leaving almost no room for intrinsic scatter at all.

A naive physical interpretation of the Tully-Fisher relation is that it connects a galaxy’s stellar mass (indicated by luminosity) to the depth of its dark matter potential well (indicated by the asymptotic circular speed). The sign

of the correlation makes perfect sense — more massive halos form more stars and make deeper potential wells — and a primordial power spectrum of index $n \approx -2$ leads to a relation of about the right form if one assumes that luminosity is proportional to dark halo mass (Faber 1982; Gunn 1982). However, this simple argument from collapse dynamics fails to explain the small scatter of Tully-Fisher because perturbations of the same mass that collapse at different times have different post-collapse densities, and hence different circular speeds (Cole & Kaiser 1989; Eisenstein & Loeb 1996). Disk asymmetries, warps, and non-circular motions all add to the scatter, making the problem even worse. Furthermore, stellar populations influence the relation between luminosity and stellar mass, the luminous matter influences the rotation curve, and rotation curves are not always flat, so even the low-level interpretation of the relation’s physical significance may be incorrect.

The collapse dynamics derivation explains Tully-Fisher in terms of cosmological initial conditions, collisionless dynamics, and an assumption that the luminosity is proportional to the mass of baryons in the pre-galactic perturbation. White & Frenk (1991) present a derivation based instead on supernova feedback, with the circular velocity of the dark halo controlling the rate at which gas is able to cool and form stars. Alternatively, the luminous component might determine the observed linewidth by modulating the inner structure of the dark halo. The last two of these explanations are nearly opposite: in one the dark matter instructs the baryons how to behave (circular velocity dictates luminosity), and in the other the baryons instruct the dark matter how to behave (luminous mass dictates linewidth). The fact that three qualitatively different arguments seem at least somewhat plausible, though none entirely satisfying, illustrates our state of confusion. I believe that when we understand (and know that we understand) the true origin of the Tully-Fisher relation, we will be much closer to understanding the essential physical processes that govern disk galaxy formation.

Persic and Salucci’s view, as I understand it, is that the Tully-Fisher relation is not in itself fundamental but is instead the consequence of more basic correlations, much as the Faber-Jackson relation is now seen as a projection of the fundamental plane for ellipticals. PHARASYN et al. explicitly set out to find a fundamental plane for spiral galaxy halos. I think this point of view is quite tenable and may well lead to useful insights. However, if we accept the common wisdom (and perhaps we should not), then the situation for ellipticals and spirals is quite different, for the central velocity dispersion of an elliptical depends mainly on the gravitational potential of the luminous matter, while the linewidth of a spiral depends mainly on the gravitational potential of the dark halo. In the former case we can use the virial theorem to connect the luminosity directly to the dynamical measure, but in the latter case we cannot. Furthermore, if the scatter in Tully-Fisher is really as small as the observations suggest, then describing Tully-Fisher as a consequence of other correlations merely shifts the problem to explaining why these other patterns are so regular. The scatter in a “halo fundamental plane” must be smaller than the Tully-Fisher scatter or it cannot “explain” Tully-Fisher in the first place, since projection can increase scatter but cannot decrease it. Even for ellipticals, the existence of a fundamental plane with small scatter does not in itself explain the Faber-Jackson

relation, for if the plane were uniformly populated by galaxies, then any off-axis projection would produce a scatterplot instead of a correlation.

Tully-Fisher surveys of the galaxy peculiar velocity field usually start with a sample that is as homogeneous as possible in order to obtain the smallest possible scatter, and hence the best possible distance estimates. For understanding galaxy formation, however, the observational desiderata in a Tully-Fisher sample are rather different: one wants a broad spectrum of galaxy types so that one can measure the full scatter at fixed linewidth and correlate residuals against galaxy morphology, surface brightness, color, environment, and so forth. Many observers are beginning to take this approach to Tully-Fisher studies and are working hard to procure and analyze the necessary data. VAN ALBADA showed results from an ambitious survey, now close to completion, that will measure extended HI rotation curves and velocity fields for 200 galaxies. DE BLOK discussed the Tully-Fisher relation for a sample of LSB spirals and concluded that they lie on the same relation as high surface brightness spirals, implying that they have systematically higher mass-to-light ratios (see Sprayberry et al. 1995; Zwaan et al. 1995; de Blok & McGaugh 1996). MATTHEWS et al. analyzed a different sample of LSB galaxies and found that they lie an average of 1.3 mag *below* the normal Tully-Fisher relation. They suggested that the difference between their result and those of Sprayberry et al. (1995) and Zwaan et al. (1995) could be accounted for by the difference between volume-limited and magnitude-limited galaxy samples, provided that the *scatter* in the Tully-Fisher relation is larger for LSB galaxies. VERHEIJEN used his beautiful Ursa Major data set to compare Tully-Fisher relations in B, I, and K for three different measures of linewidth (W_{HI} , $2V_{\text{max}}$, and $2V_{\text{flat}}$). While the combination of K magnitudes and V_{flat} linewidths yielded the smallest scatter, other combinations were not radically different. HENDRY found that he could obtain a modest (but only modest) reduction in Tully-Fisher scatter for a different data set by using the velocity at 0.65 optical radii in place of the “asymptotic” velocity, or by using a template fit to the Persic et al. (1996) universal rotation curve. RHEE described a principal component analysis of galaxy rotation curves that may ultimately lead to new formulations of the Tully-Fisher relation and new dynamical quantities to correlate residuals against. BERSHADY presented Tully-Fisher results for a sample of galaxies at moderate redshift. I can’t say that this wealth of new observations has yet led to any grand synthesis (for me, anyway), but it is clear that the data environment for examining the Tully-Fisher relation and its implications for galaxy formation is getting much richer.

8. Observational Prospects

The key observational results reported at DM 1996 come from an impressive variety of instruments and techniques. The Keck telescope is making dramatic progress on problems that were previously inaccessible, such as the deuterium searches described by TYTLER. The Hobby-Eberly telescope will join Keck later this year (BERSHADY), and other large aperture telescopes will follow in the near future. Big telescopes with high-quality spectrographs are revolutionizing the study of galaxy evolution, especially in combination with multi-color selection of high-redshift galaxies (FONTANA) and with HST imaging, which can reveal the

morphology of galaxies at intermediate redshifts (FILIPPI et al.) and measure number counts and angular sizes to extremely faint magnitudes.

In the areas of galaxy structure and dark matter, the most important results are coming from innovative, ambitious applications of smaller optical telescopes and aperture synthesis radio arrays. These include “traditional” microlensing searches (FREEMAN) and studies of “pixel” microlensing (CROTTS; GONDOLO), quasar microlensing (HAWKINS), and weak lensing (BROADHURST), which take advantage of the wide fields and monitoring capabilities afforded by CCD cameras on moderate-sized telescopes. This list has a rather obvious moral: gravitational lensing (including old-fashioned macrolensing, as discussed by DANZIGER and RIX) is an excellent tool for studying dark matter because it responds directly to mass. We will also learn a great deal from extensive, systematic surveys that combine optical/IR imaging with optical spectroscopy and/or HI mapping (BROEILS; VERHEIJEN; VAN ALBADA; DE BLOK).

We have many other observational developments to look forward to in the next few years. I have already mentioned the hope for a consensus on primordial deuterium, and from it a measurement of the cosmic baryon density. There is also the possibility that accelerators or detection experiments will turn up a compelling candidate for non-baryonic dark matter. The study of galaxy structure will be advanced enormously by the photometry and spectroscopy of the Sloan Digital Sky Survey (see Gunn & Weinberg 1995), which will provide for millions of galaxies the kind of data that are available for hundreds today. Better constraints on cosmological parameters and theories of structure formation will emerge from giant redshift surveys (the Sloan survey and the Anglo-Australian, 2-Degree Field survey), from the Ly α forest, and from ground- and balloon-based observations of microwave background anisotropies. In the slightly longer term, the planned microwave background satellites — if they produce results that accord with current theoretical expectations — will yield precise measurements of cosmological parameters and initial conditions, and we will be left to work out how these lead to observed galaxies.

At the end of our meeting, Persic and Salucci suggested that we mark our calendars for DM 2000. If the developments of the next four years are as striking as those of the last four, we can expect either to have a much firmer understanding of galaxy structure, dark matter, and galaxy formation, or to be rather deeply puzzled.

Acknowledgments. I am grateful to Massimo Persic and Paolo Salucci for organizing a superb conference and for inviting me to give this summary report. I am grateful to all of the participants for providing so much interesting material to summarize! I thank Hans-Walter Rix for many stimulating discussions during the conference, and, above all, for guiding me on a fabulous pre-conference trip through the Dolomites, thus making it possible for me to concentrate on the talks. I also thank Andy Gould for many enlightening conversations about MACHOs, MOND, and dark matter.

References

Adams, F. C., & Laughlin, G. 1996, *ApJ*, 468, 586

- Bahcall, J. N., Flynn, C., Gould, A., & Kirhakos, S. 1994, *ApJ*, 435, L51
- Bernstein, G. M., Guhathakurta, P., Raychaudhury, S., Giovanelli, R., Haynes, M. P., Herter, T., & Vogt, N. P. 1994, *AJ*, 107, 1962
- Brainerd, T. G., Blandford, R. D., & Smail, I. 1996, *ApJ*, 466, 623
- Burles, S. & Tytler, D. 1996, *Science*, submitted, astro-ph/9603070
- Casertano, S. & van Gorkom, J. H. 1991, *AJ*, 101, 1231
- Cen, R., Miralda-Escudé, J., Ostriker, J. P., & Rauch M. 1994, *ApJ*, 427, L9
- Charlot, S. & Silk, J. 1995, *ApJ*, 445, 124
- Cole, S., Aragon-Salamanca, A., Frenk, C. S., Navarro, J. F., & Zepf, S. E. 1994, *MNRAS*, 271, 744
- Cole, S. & Kaiser, N. 1989, *MNRAS*, 237, 1127
- Cowie, L. L., Songaila, A., Kim, T., & Hu, E. M. 1995, *AJ*, 109, 1522
- Courteau, S., De Jong, R., & Broeils, A. 1996, *ApJ*, 457, L73
- De Blok, W. J. G. & McGaugh, S. S. 1996, *ApJ*, 469, L89
- Dubinski, J. & Carlberg, R. G. 1991, *ApJ*, 378, 496
- Eisenstein, D. J. & Loeb, A. 1996, *ApJ*, 459, 432
- Evrard, A. E., Summers, F. J. & Davis, M. 1994, *ApJ*, 422, 11
- Faber, S. M. 1982, in *Astrophysical Cosmology*, eds. H. A. Brück et al., (Vatican City: Pontifical Academy), 191
- Flores, R. A. & Primack, J. R. 1994, *ApJ*, 427, L1
- Flynn, C., Gould, A., & Bahcall, J. N. 1996, *ApJ*, 466, L55
- Gunn, J. E. 1982, in *Astrophysical Cosmology*, eds. H. A. Brück et al., (Vatican City: Pontifical Academy), 233
- Gunn, J. E. & Weinberg, D. H. 1995, in *Wide Field Spectroscopy and the Distant Universe*, eds. S. Maddox & A. Aragón-Salamanca, (Singapore: World Scientific), 3, astro-ph/9412080
- Hernquist, L. H., Katz, N., Weinberg, D. H., & Miralda-Escudé, J. 1996, *ApJ*, 457, L51
- Katz, N. 1992, *ApJ*, 391, 502
- Katz, N. & Gunn, J. E. 1991, *ApJ*, 377, 365
- Katz, N., Hernquist, L. & Weinberg, D. H. 1992, *ApJ*, 399, L109
- Katz, N., Weinberg, D. H., & Hernquist, L. 1996, *ApJS*, 105, 19
- Kauffmann, G., Charlot, S., & White, S. D. M. 1996, *MNRAS*, submitted, astro-ph/9605136
- Kauffmann, G., White, S. D. M., & Guideroni, B. 1993, *MNRAS*, 264, 201
- Lilly, S. J., Le Fevre, O., Crampton, D., Hammer, F., & Tresse, L. 1995, *ApJ*, 455, 50
- Meyer, D. M. & York, D. G. 1987, *ApJ*, 315, L5
- Milgrom, M. 1983, *ApJ*, 270, 365
- Moore, B. 1994, *Nature*, 370, 629
- Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, *ApJ*, 462, 563 (NFW)
- Navarro, J. F. & Steinmetz, M. 1996, *ApJ*, submitted, astro-ph/9605043

- Navarro, J. F. & White, S. D. M. 1994, MNRAS, 267, 401
- Olling, R. 1996a, AJ, 112, 457
- Olling, R. 1996b, AJ, 112, 481
- Paczynski, B. 1986, ApJ, 304, 1
- Persic, M., & Salucci, P. 1991, ApJ, 368, 60
- Persic, M., Salucci, P., & Stel, F. 1996, MNRAS, 281, 27
- Press, W. H. & Schechter, P.L. 1974, ApJ, 187, 425
- Rugers, M. & Hogan, C. J. 1996a, ApJ, 459, L1
- Rugers, M. & Hogan, C. J. 1996b, AJ, 111, 2135
- Salucci, P. & Frenk, C. S. 1989, MNRAS, 237, 247
- Sprayberry, D., Bernstein, G. M., Impey, C. D., & Bothun, G. D. 1995, ApJ, 438, 72
- Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17
- Steinmetz, M. 1995, MNRAS, 276, 549
- Strauss, M. A. & Willick, J. A. 1995, Phys Rep, 261, 271
- Summers, F. J., Davis, M., & Evrard, A. E. 1995, ApJ, 454, 1
- Theuns, T. & Warren, S. J. 1996, MNRAS, in press, astro-ph/9609076
- Tytler, D., Fan, X.-M., & Burles, S. 1996, Nature, 381, 207
- Valdes, F., Jarvis, J. F., Mills, A. P., & Tyson, J. A. 1984, ApJ, 281, L59
- Vedel, H., Hellsten, U. & Sommer-Larsen, J. 1994, MNRAS, 271, 743
- Walker, T. P., Steigman, G., Kang, H. S., Schramm, D. N., & Olive, K. A. 1991, ApJ, 376, 51
- Weinberg, D. H., Hernquist, L., Katz, N. S., & Miralda-Escudé, J. 1996, in Cold Gas at High Redshift, eds. M. Bremer et al. (Dordrecht: Kluwer), 93, astro-ph/9512016
- White, S. D. M. 1996, in Gravitational Dynamics, eds. O. Lahav et al., (Cambridge: Cambridge Univ. Press), astro-ph/9602021
- White, S. D. M. & Frenk, C. S. 1991, ApJ, 379, 52
- White, S. D. M., Navarro, J. F., Evrard, A. E., & Frenk, C. S. 1993, Nature, 366, 429
- White, S. D. M. & Rees, M. J. 1978, MNRAS, 183, 341
- Wilczek, F. 1997, in Critical Dialogues in Cosmology, ed. N. Turok, (Singapore: World Scientific), astro-ph/9608285
- Womble, D. S., Sargent, W. L. W., & Lyons, R. S. 1996, in Cold Gas at High Redshift, eds. M. Bremer et al., (Dordrecht: Kluwer), astro-ph/9511035
- Zabludoff, A., Zaritsky, D., Lin, H., Tucker, D., Hashimoto, Y., Schechter, S. A., Oemler, A., & Kirshner, R. P. 1996, ApJ, 466, 104
- Zaritsky, D., Smith, R., Frenk, C., & White, S. D. M. 1993, ApJ, 405, 464
- Zaritsky, D. & White, S. D. M. 1994, ApJ, 435, 599
- Zhang, Y., Anninos, P., & Norman, M. L. 1995, ApJ, 453, L57
- Zwaan, M. A., van der Hulst, J. M., De Blok, W. J. G., & McGaugh, S. S. 1995, MNRAS, 273, 35

9. Appendix: The Dark Matter Rap

I composed “The Dark Matter Rap: A Cosmological History for the MTV Generation” in the fall of 1992, and I first performed it at the Institute for Advanced Study’s Tuesday Lunch on December 8 of that year. I have avoided circulating the lyrics in the past mainly because I think the piece (I hesitate to call it a “song”) is much more fun to hear or to see performed than it is to read. However, by now I’ve performed it *ad sufficient nauseam* that a good fraction of its potential international audience has heard it at least once. Since I did close my conference summary with it and could probably never find a more appropriate opportunity to publish the text, I have decided to include it here. I hope that someday soon I will get around to installing an audio version on my WWW page (<http://www-astronomy.mps.ohio-state.edu/~dhw/>), so I encourage readers who haven’t heard this folly, live or taped, to try there before reading any further. I have resisted the temptation to include references, since I chose names with as much attention to rhyme and meter as to historical accuracy.

My name is Fritz Zwicky,
I can be kind of prickly,
This song had better start
by giving me priority.
Whatever anybody says,
I said in 1933.
Observe the Coma cluster,
the redshifts of the galaxies
imply some big velocities.
They’re moving so fast,
there must be missing mass!
Dark matter.

Dark matter: Do we need it? What is it? Where is it? How much?
Do we need it? Do we need it? Do we need it? Do we need it?

For nearly forty years,
the dark matter problems sits.
Nobody gets worried ’cause, “It’s only crazy Fritz.”
The next step’s not ’til the early 1970s,
Ostriker and Peebles,
dynamics of the galaxies,
cold disk instabilities.
They say: “If the mass, were sitting in the stars,
all those pretty spirals, ought to be bars!
Self-gravitating disks? Uh-uh, oh no.
What those spirals need is a massive halo.
And hey, look over here, check out these observations,
Vera Rubin’s optical curves of rotation.
They can provide our needed confirmation:
those curves aren’t falling, they’re FLAT!
Dark matter’s where it’s AT!

Dark matter: Do we need it? What is it? Where is it? How much?
What is it? What is it? What is it? What is it?

And so the call goes out for the dark matter candidates:
black holes, snowballs, gas clouds, low mass stars, or planets.
But we quickly hit a snag because galaxy formation
requires too much structure in the background radiation
if there's only baryons and adiabatic fluctuations.
The Russians have an answer: "We can solve the impasse.
Lyubimov has shown that the neutrino has mass."
Zel'dovich cries, "Pancakes! The dark matter's HOT."
Carlos Frenk, Simon White, Marc Davis say, "NOT!
Quasars are old, and the pancakes must be young.
Forming from the top down it can't be done."
So neutrinos hit the skids, and the picture's looking black.
But California laid-back, Blumenthal & Primack
say, "Don't have a heart attack.
There's lots of other particles.
Just read the physics articles.
Take this pretty theory that's called supersymmetry.
What better for dark matter than the L-S-P?
The mass comes in at a $\sim \text{keV}$,
and that's not hot, that's warm."
Jim Peebles says, "Warm? Don't be half-hearted.
Let's continue the trend that we have started.
I'll stake out a position that's bold:
dark matter's not hot, not warm, but COLD."
Well cold dark matter causes overnight sensations:
hand-waving calculations,
computer simulations,
detailed computations of the background fluctuations.
Results are good, and the prospects look bright.
Here's a theory that works! Well, maybe not quite.

Dark matter: Do we need it? What is it? Where is it? How much?
Where is it? How much? Where is it? How much?

We have another puzzle that goes back to Robert Dicke.
Finding a solution has proven kind of tricky.
The CMB's so smooth, it's as if there'd been a compact
between parts of the universe that aren't in causal contact.
Alan Guth says, "Inflation,
will be our salvation,
give smoothness of the universe a causal explanation,
and even make the galaxies from quantum fluctuations!
There is one prediction, from which it's hard to run.
If inflation is correct, then Omega should be one."
Observers say, "Stop, no, sorry, won't do.
Look at these clusters, Omega's point 2."

The theorists respond, "We have an explanation.
 The secret lies in biased galaxy formation.
 We're not short of critical mass density.
 Just some regions are missing luminosity."
 Observers roll their eyes, and they start to get annoyed,
 But the theorists reply, "There's dark matter in the voids."
 Dark matter: Do we need it? What is it? Where is it? How much?
 Do we need it? Do we need it? Do we need it? Do we need it?

Along comes Moti Milgrom,
 who's here to tell us all:
 "This dark matter claptrap
 has got you on the wrong track.
 You're all too mired in conventionality,
 wedded to your standard theory of gravity,
 seduced by the elegance of General Relativity.
 Just change your force law, that's the key.
 Give me one free parameter, and I'll explain it all."
 "Not so," claim Lake, and Spergel, et al.,
 "On dwarf galaxies, your theory does fall."
 The argument degenerates; it's soon a barroom brawl.

Dark matter: Do we need it? What is it? Where is it? How much?
 What is it? What is it? What is it? What is it?

New observations hit the theory like an ice cold shower.
 They show that cold dark matter has too little large scale power.
 Says Peebles: "Cold dark matter? My feeblest innovation.
 An overly aesthetic, theoretical aberration.
 Our theories must have firmer empirical foundation.
 Shed all this extra baggage, including the carry-ons.
 Use particles we know, i.e., the baryons.
 Others aren't convinced, and a few propose a mixture
 of matter hot and cold, perhaps with strings or texture.
 And nowadays some physicists are beginning to wonder
 if it's time to resurrect Einstein's "greatest blunder."
 Why seek exotic particles instead of just assume
 that the dark matter's all around us – it's what we call the vacuum?
 Who's right? It's hard to know, 'til observation or experiment
 gives overwhelming evidence that relieves our predicament.
 The search is getting popular as many realize
 that the detector of dark matter may well win the Nobel Prize.
 So now you've heard my lecture, and it's time to end the session
 with the standard closing line: Thank you, any questions?

- DW, 12/92